23 Biological Effects of Ionizing Radiation

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23.1 Introduction

The main tool in nuclear medicine is ionizing radiation; therefore it is important for its users to be familiar with its biological effects and pathophysiological basis. Ionization is the process of ion production by ejection of electrons from atoms and molecules after exposure to high temperature, electrical discharges or electromagnetic and nuclear radiation. Ionizing radiation is subdivided into electromagnetic radiation (X-rays and gamma rays) and particulate radiation including neutrons and charged particles (alpha and beta particles).

Exposure to ionizing radiation comes from several natural and man-made sources (Table 23.1). The nuclear medicine professional should be able to provide information to the patient and the public about the radiation risks from these sources and to provide a comparison of exposure from medical procedures to natural sources. Biological effects of ionizing radiation depend on several factors that make them variable and inconsistent. The effects are classified based on their nature and timing after exposure into early or delayed, somatic or hereditary, stochastic or deterministic (Fig. 23.1). Stochastic effects refer to random and unpredictable

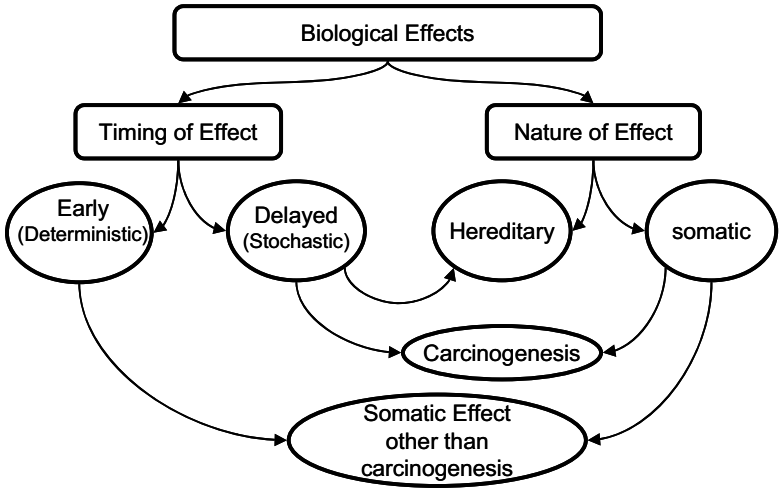

Fig. 23.1. The various biological effects of ionizing radiation. The effects can be classified into early or deterministic, which have a threshold, and delayed or stochastic, with no threshold. Effects are also classified into somatic and hereditary. The somatic include early and delayed effects (cancer)

Table 23.1. Sources of ionizing radiation

Natural sources	Man-made sources
External radiation – Cosmic rays – Terrestrial radiation (radioactive material in rocks, such as potassium-40) Internal radiation – Inhalation (Radon gas) – Ingestion	Medical Occupational Nuclear power Nuclear explosions Nuclear accidents

effects usually following chronic exposure to low dose radiation. Hereditary effects and carcinogenesis following diagnostic imaging is of a stochastic nature.

Deterministic (non-stochastic) effects are non-random and have a highly predictable response to radiation. There is a threshold of radiation dose after which the response is dose-related. Some of the known deterministic effects are radiation-induced lung fibrosis and cataract.

23.2 Mechanisms of Radiation Effects

Ionizing radiation exerts its effects on biological targets through two major mechanisms [1, 2], direct and indirect (Fig. 23.2).

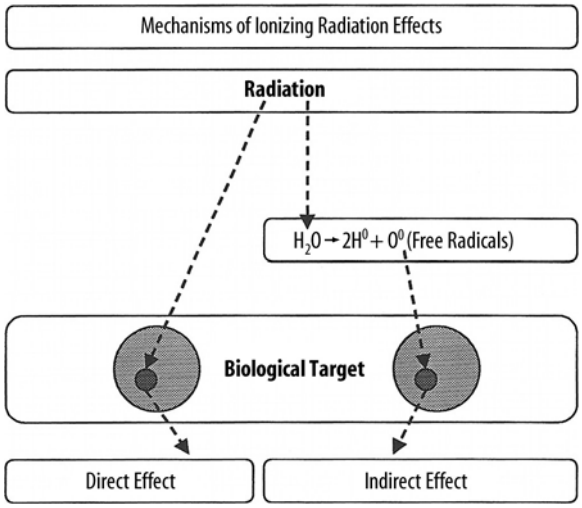

Fig. 23.2. The two mechanisms of ionizing radiation effects on biological tissue, the direct, or target, mechanism and the indirect, through production of free radicals that consequently cause damage

23.2.1 Direct Effect

The direct effect theory or target theory proposes that ionizing radiation acts by direct hits on target atoms. All atoms or molecules within the cells, such as enzymatic and structural proteins and RNA, are vulnerable to radiation injury. DNA, however, is the principal target, in which ionizing radiation produces single- or double-stranded chromosomal breaks.

23.2.2 Indirect Effect

The direct mechanism theory was found to be inadequate in explaining cellular radiation injuries. The indirect theory proposes that ionizing radiation exerts its effect via radiolysis of cellular water, forming free radicals. These free radicals interact with atoms and molecules within the cells, particularly DNA, to produce chemical modifications and consequently harmful effects. When X-rays interact with water two types of free radicals are formed:

$$H^o \rightarrow H^o \text{ (hydrogen)} + OH^o \text{ (hydroxy)}$$

The presence of an excess of oxygen during irradiation of cells allows the formation of additional free radicals:

$$H^o + O_2 \rightarrow HO_2{}^o \text{ (hydroxyperoxy free radicals)}$$
$$HO_2{}^o + HO_2{}^o \rightarrow H_2O_2{}^o + O_2$$

It is worth noting that antioxidants block hydroxyperoxy free radical combination into the highly unstable hydrogen peroxide.

It has been estimated that about two-thirds of biological damage caused by low linear energy transfer (LET) radiation is due to indirect action [3]. Biological damage by high LET is primarily by direct ionization action. Figure 23.3 illustrates how radiation leads to tissue damage.

Radiation effects have been observed in extents beyond that explained by effects exerted on directly irradiated cells. Cells in temporal or spatial distance from the initial radiation insult have been shown to have delayed effects of radiation. Two phenomena are described: the bystander effect and genomic instability.

Bystander Effect. The cells in the vicinity of irradiated cells show effects that cannot be attributed to targeting by ionizing radiation tracks. Additionally, when cells are irradiated and later transferred to another medium, the cells in proximity in the new medium exhibit DNA damage, mutation and carcinogenesis. Through cell-to-cell interaction, the directly irradiated cells communicate with adjacent cells and spread the effect of radiation to a larger number of cells. The mechanism

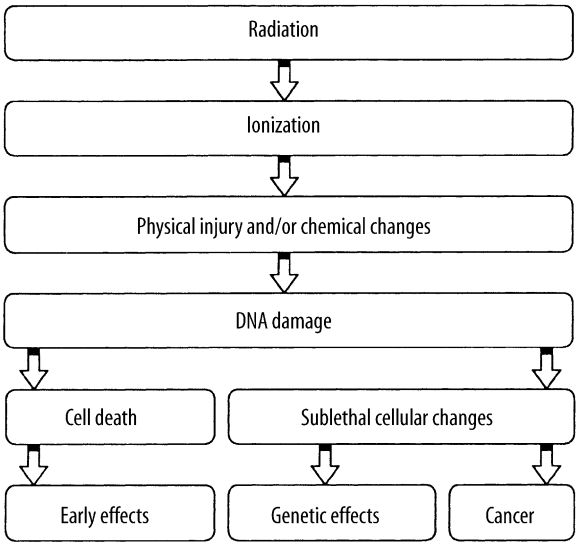

Fig. 23.3. Intracellular changes induced by ionizing radiation that lead to cell damage

is not clearly understood; however, gap junctional intercellular communication [4] or release of soluble factors (such as cytokines) [5] from irradiated cells has been proposed. The bystander effect has been mainly described for densely ionizing radiation (such as alpha particles) [6], but also is seen in low LET radiation (such as gamma or X-rays).

Genomic Instability. Maximal radiation-induced genetic damage is formed shortly (minutes to hours) after radiation exposure. Nevertheless, it has been observed that not only the irradiated cells but also descendents may show delayed effects. Cells that sustain non-lethal DNA damage show increased mutation rate in descendent cells several generations after the initial exposure [7]. Delayed effects include delayed reproductive death up to six generations following the primary insult [8].

23.3 Factors Affecting Radiation Hazards

Radiation injury can be modified by factors related to the ionizing radiation and the target tissue.

23.3.1 Factors Related to Ionizing Radiation

Certain factors related to radiation itself determine the various effects for the same radiation dose to biological organs.

Type of Radiation. Various types of radiation differ in penetrability based on LET, which expresses energy loss per unit distance travelled (kiloelectron volts per micrometer). This value is high for alpha particles, lower for beta particles, and even less for gamma rays and X-rays. Thus alpha particles penetrate a short distance but induce heavy damage, whereas beta particles travel a longer distance but much shorter than gamma rays.

Mode of Administration. The radiation dose is obviously an important factor. In addition, a single dose of radiation causes more damage than the same dose being divided (fractionated). Collectively these two factors are expressed as dose per fraction.

Dose Rate. Dose rate expresses the time for which dose is administered. The longer the duration for the same total dose, the better the chance of cellular repair and the smaller the damage.

23.3.2 Factors Related to Biological Target

Certain properties of tissues and cells can significantly modify the biological effects of ionizing radiation.

Radiosensitivity. Although all cells can be affected by ionizing radiation, normal cells and their tumors vary in their sensitivity to radiation. Slowly and rapidly growing cells have different radiosensitivity in relation to their movement through the cell cycle. Radiosensitivity varies with the rate of mitosis and cellular maturity. Blood-forming cells are very sensitive to radiation, while neurons, muscle and parathyroid cells are highly radioresistant. Within a given cell, the nucleus in general is relatively more radiosensitive than the cytoplasm. When cells in G_0/G_1 phase of the cell cycle are exposed to radiation they tend to halt their progression into G_2/M phase. G_2 synchronization produces a cluster of radiosensitive cells. A second hit within a time frame of 5–12 h leads to a higher proportion of deleterious effects. This is expected for radioisotopes with sequential alpha or beta decay as in $^{90}Sr/^{90}Y$ [9].

Repair Capacity of Cells. Some cells are known to have a higher capacity than others to repair the damage caused by ionizing radiation; consequently, the biological effects of the same radiation dose are different. Significant repair is known to occur quickly, within 3 h.

Cell-Cycle Phase. The life cycle of the cell includes several phases: the pre-DNA synthetic phase (G_1), the DNA synthetic phase (S), the post-DNA synthetic phase (G_2), mitosis (M), and the more recently identified phase of no growth (0), which represents the time after mitosis to the start of the G_1 phase. All phases of the cell cycle can be affected by ionizing radiation. The radiosensitivity of a given cell varies from one cell-cycle phase to another. Overall, sensitivity appears to be

greatest in G_2 phase; irradiation during this phase retards the onset of cell division. Irradiation during mitosis induces chromosomal aberrations, i.e., breaks, deletions, translocations, and others. The sensitivity of a given cell-cycle phase also differs from one cell type to another and by alteration of radiation injury [3]. For example, the reproductive cells are most sensitive during the M phase, while damage to DNA synthesis and chromosomes occurs mostly when the cell is in the G_2 phase. Recovery from sublethal damage occurs in all phases of the cell cycle. However, this is most pronounced in the S phase, which is also the most radioresistant phase [10].

Degree of Tissue Oxygenation. Molecular oxygen is known to have the ability to potentiate the response to radiation; this is known as the oxygen effect. The amount of molecular oxygen rather than the rate of oxygen utilization by the cells is the most important factor for increasing the sensitivity of cells to radiation. The probable mechanism is the allowance of additional free radicals, which enhance the damage of cells [10].

23.4 Radiation-Induced Cell Injury

In general, an injury which has a high chance of repair is sublethal, that which can be repaired with treatment is potentially lethal, and that which is permanent is lethal. The nucleus is relatively more radiosensitive than the cytoplasmic structures. Nuclear changes after radiation include swelling of the nuclear membrane and disruption of chromatin materials. Cytoplasmic changes include swelling, vacuolization, disintegration of mitochondria and endoplasmic reticulum, and reduction in the number of polysomes [2, 10]. Depending on the dose of radiation and the subcellular changes, along with the previously described factors, the potential effects on the cell vary (Table 23.2). After ionizing radiation exposure, cellular injury occurs in one of the following forms [11]:

1. Division delay: after exposure to radiation in the range of 0.5 – 3 Gy delayed mitosis is observed; however, near normal restoration of mitotic activity is achieved following several generations.
2. Reproductive failure: the failed mitotic activity is permanent and eventually cell death ensues. This is observed in a linear fashion after exposure to more than 1.5 Gy. Below this level the reproductive failure is random in nature and nonlinear.
3. Interphase death: apoptosis, or programmed cell death, is defined as a particular set of microscopic changes associated with cell death. Radiation-induced apoptosis is highly related to the type of involved cell. Lymphocytes, for example, are highly susceptible to radiation by this mechanism.

23.5 Various Effects of Radiation

The biological effect of low-level radiation is extremely difficult to study in a controlled environment. The effects of high radiation exposure to populations during accidents or nuclear war have been the main source of information.

At low doses, radiation can trigger only partially understood effects that can lead to cancer or genetic damage. These effects take years or generations to appear. At high doses, the effect may become evident within minutes, hours, or days. It is important for physicians to be familiar with the early effects of high radiation doses (1 Gy or more to the whole body), since the possibility that people may be exposed to such doses is increasing.

23.5.1 Dose-Response Models

There are many models predicting relationships between the radiation dose and the effect of such an exposure to a biological target. The differences between these models arise from different underlying assump-

Table 23.2. Types of cellular damage in relation to approximate radiation dose. (Modified from [3] with permission)

Dose [Grays (rads)]	Type of damage	Comments
0.01 – 0.05 (1 – 5)	Mutation (chromosomal aberration, gene damage)	Irreversible chromosome breaks, may repair
1 (100)	Mitotic delay, impaired cell function	Reversible
3 (300)	Permanent mitotic inhibition, impaired cell function, activation and deactivation of cellular genes and oncogenes	Certain functions may repair; one or more divisions may occur
>4 – 10 (>400 – 1000)	Interphase death	No division
500 (50,000)	Instant death	No division Proteins coagulate

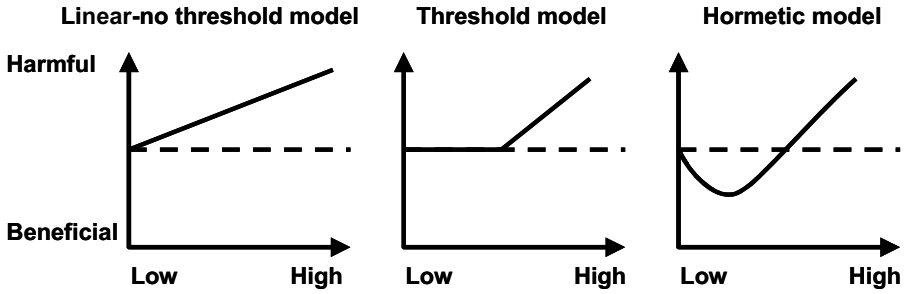

Fig. 23.4. Comparison between three different dose-response models. The *dashed line* represents health effects in the absence of radiation. *y*- and *x*-axes represent health effects and radiation dose, respectively. (Reproduced from [12] with permission)

tions. Figure 23.4 illustrates three models describing the response of a biological system to various radiation doses.

1. Linear-No Threshold Model. This model assumes that any level of radiation is harmful and that the risk increases linearly with increments of dose. This model is applied for radiation protection purposes and is meant to limit the risk to workers in radiation fields.
2. Threshold Model. This model assumes that the risk of radiation is linearly related to the dose; however, this occurs only after a certain threshold level is exceeded. Below the threshold level no risk is to be expected. The theory behind the threshold level is that some degree of cellular damage should accumulate and produce cell damage.
3. Hormesis Model. In this model there is a bimodal effect of radiation, where below a certain threshold level radiation is protective, and harmful effects are seen only when this threshold is exceeded. The rationale is that radiation at low levels induces protective cellular mechanisms which prevent DNA damage occurring spontaneously or due to other stresses [13, 14] (Fig. 23.5).

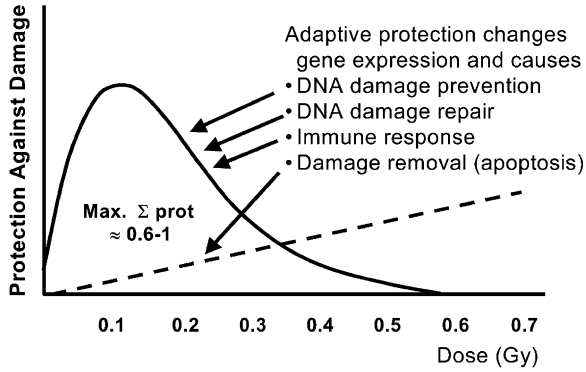

Fig. 23.5. Low-dose (low-LET) induced adaptive protection. Scheme of dose response function. (Reproduced with permission from [15])

23.5.2 Early Radiation Effects

23.5.2.1 Acute Whole-Body Exposure Syndromes

Following exposure to a large, single, short-term whole-body dose of ionizing radiation, the resulting injury is expressed as a series of clinical symptoms. The sequence of events can be generally divided into four clinical periods:

1. The prodromal period, up to 48 h, when the symptoms include anorexia, nausea, vomiting, and diarrhea
2. The latent period, from 48 h to 2 – 3 weeks after exposure, when the patient becomes asymptomatic
3. The manifest phase, from week 6 to week 8 after exposure, when variable symptoms appear based on the radiation dose
4. The recovery period: if the patient survives, recovery occurs from 6 weeks to several months after exposure.

The presentation of these periods and their duration depends on the amount of radiation exposure [2, 3]. In general, about half of those who receive doses of 2 Gy suffer vomiting within 3 h, and symptoms are rare after doses below 1 Gy. With a sufficiently high radiation dose, acute radiation sickness may result. Additional symptoms related to specific organ injury may occur, based on the dose, and can be divided according to the known acute radiation syndromes:

Radiation Sickness. The symptoms can be mild, such as loss of appetite and mild fatigue, or evident only on laboratory tests with mild lymphopenia (subclinical), or may be severe, appearing as early as 5 min after exposure to very high doses of 10 Gy or more and also include fatigue, sweating, fever, apathy, and low blood pressure. Lower doses delay the onset of symptoms and produce less severe symptoms or a subclinical syndrome that can occur with doses of less than 2 Gy to the whole body, and recovery is complete with 100% survival.

Hematopoietic (Bone Marrow) Syndrome. This occurs at higher doses of more than 1.5 – 2 Gy to the whole

body. With doses up to 4 Gy, a radiation prodrome is seen, followed by a latent period of up to 3 weeks. The clinical effects are not seen for several weeks after the radiation dose, when anemia, petechiae, increased blood pressure, fatigue, ulceration in the mouth, epilation, purpura, and/or infection appear. At doses in the order of 4 – 8 Gy, a modified bone marrow syndrome occurs. The initial problem is more severe, the latest period is shortened, and the manifest illness is more severe. Death is possible due to bleeding with exposure in this dose range.

Gastrointestinal Syndrome. This syndrome occurs with still higher doses of 6 – 10 Gy which cause manifestations related to the gastrointestinal tract in addition to those of the bone marrow syndrome. Initially, loss of appetite, apathy, nausea, and vomiting occur for 2 – 8 h. These effects may subside rapidly. Several days later, malaise, anorexia, nausea, vomiting, high fever, persistent diarrhea, abdominal distention, and infections appear. During the second week of irradiation, severe dehydration, hemoconcentration, and circulatory collapse may be seen, eventually leading to death.

Central Nervous System Syndrome. The central nervous system is generally resistant to radiation effects. A dose higher than 10 Gy is required to cause substantial effects on the brain and the nervous system. Symptoms include intractable nausea and vomiting, confusion, convulsions, coma, and absent lymphocytes. The prognosis is poor, with death in a few days.

23.5.2.2 Acute Regional Effects

When enough radiation is delivered locally to a certain part of the body, as in the case of radiation therapy, which focuses on a certain field, acute effects can appear in the exposed area. Examples include skin erythema and gastrointestinal edema and ulceration.

23.5.3 Delayed Radiation Effects

There is considerable debate over the effects of low level radiation. On the one hand, there are several theories and reports describing the harmful effects of low level radiation and how underestimated the risks are. At the other extreme, there are theories and reports of harmless and even potentially useful effects of exposure to such levels of radiation.

The theories describing the effects of low level radiation and the projected risk estimates of cancer development or genetic effects in humans are purely mathematical and not actual observations. The data from populations exposed to high level radiation were extrapolated to determine the likelihood of these events at low level radiation exposure. Such events in any given population occur at extremely low rates and to further complicate the issue after long latency periods; therefore solid epidemiological data are difficult to obtain.

23.5.3.1 Cancer

Cancer is the most important concern of radiation. It has been recognized for more than 90 years that ionizing radiation causes cancers. Tissues with a high rate of cell proliferation are more prone to radiation tumor induction. Cancer becomes evident only long after the first damage is done, following a period of latency. Leukemia first appears at least 2 – 5 years after exposure while solid tumors appear after at least 10 years, often several decades later. The tumors reported to be associated with radiation include leukemia, multiple myeloma, and cancers of the breast, colon, thyroid, ovary, lung, urinary bladder, stomach, CNS (other than brain), and esophagus.

There is no clear evidence that low-level radiation causes cancer. Holm et al. [16] studied 6000 patients given a diagnostic dose of iodine-131. There was no increase in the incidence of thyroid cancer in this population, including a subset of 2000 children. Saenger et al. [17] also studied 2000 patients treated with iodine-131 in doses of up to several hundreds of MBq with 20 years follow-up. The incidences of thyroid cancer and leukemia were identical to those among patients treated surgically for the same conditions.

To complicate the issue further, recently acquired data minimize the effects of low-level radiation in the induction of cancer and even suggest that such levels of radiation exposure may be useful [18, 19]. DNA mutations unrelated to radiation are produced continuously. It is estimated that each day the intrinsic human metabolism produces 240,000 DNA mutations in each cell of the body [20]. During youth, these are repaired and, in general, cancer occurs infrequently. With old age, the capability to repair may decrease and cancer appears more frequently. A high dose of 2 Gy adds 4000 (20 mutations/cGy) to the daily 240,000 mutations. Ward [10, 21] determined that a low radiation dose of 0.2 Gy stimulates repair by 50% – 100% and adds only 400 mutations to the intrinsic 240,000 mutations. It is the reduced ability of our repair mechanism to correct the very high background of intrinsic mutations that increases the risk of developing cancer. Genetic impairment of DNA repair capacity results in death from cancer at an early age. Loss of DNA repair capacity with age increases the risk of cancer. Exposure to high doses of radiation similarly reduces the repair capacity of cellular DNA and increases the risk of cancer [22, 23] (see chapter on oncology).

23.5.3.2 Genetic Effects

Genetic effects may include changes in the number and structure of chromosomes and gene mutations, dominant or recessive. They depend on the following factors:

1. The stage of germ cell development: Immature germ cells appear to be capable of repair, while in mature germ cells there is little or no repair (Table 23.3).
2. Dose rate: The repair process starts simultaneously with radiation damage. The damage with a high dose rate is greater; lower dose rates produce fewer mutations. At a low-intermediate dose rate the time period is an important factor as far as the final outcome of the radiation injuries is concerned. However, this does not hold true in the case of a high radiation rate, where the repair process is minimal due to the direct action of injury.
3. Dose fractionation: The time interval between fractions is very important for the frequency of mutations. The number of translocations will be reduced by dose fractionation; however, the incidence of mutations will not be affected by increasing the time interval between fractions.
4. Interval between exposure and conception: The frequency of mutation is very low if conception occurs after 7 weeks, but it is high when the interval between radiation exposure and conception is 7 weeks or less.

23.5.3.3 Effects on the Unborn Child

The embryonic stage is one of the most radiosensitive stages in the life of any organism. The classical triad of effects of radiation on the embryo is growth retardation, embryonic, fetal, or neonatal death, and congenital malformation. The probability of finding one or more of these effects is dependent upon radiation dose, the dose rate, and the stage of gestation at exposure. Stage of development is particularly important, since the organ which is differentiated at that time will be most vulnerable; this determines the type of abnormality or malformation that will be observed. During the first 2 weeks of conception the effect of radiation is an all or none effect, where the embryo is aborted. Following this period and up to 8 weeks the embryo is very vulnerable to congenital malformations. Organogenesis starting then might lead to mental retardation, congenital malformation as well as organ-specific effects. For example, radioactive iodine administered to a pregnant mother who passed 10 – 13 weeks of gestation will cross the placenta and accumulate in the already formed fetal thyroid. A summary of the possible effects from irradiation at various stages of gestation is shown in Table 23.3.

Table 23.3. Effects of radiation on the unborn child

Stage of gestation (days)	Possible effects
1 – 9	Death of embryo is most likely, with little chance of malformation
10 – 12	Reduced lethal effect with still little chance of malformation
13 – 56	Production of congenital malformation and retarded growth
57 – 112	Extreme mental retardation (time of most severe effect on CNS)
113 – 175	Less frequent effect on CNS
After 175	Very low frequency of CNS effects (no reported case of severe retardation)

Development of cancer at an early age is controversial. Studies have suggested an increased risk of hematopoietic and solid tumors at an early age [24, 25]. However, a comparison between individuals whose parents were exposed to radiation during the atomic bombing of Hiroshima and Nagasaki and those whose parents were not showed no significant differences in a large number of variables including congenital effects, still births, and cancer at an early age.

23.5.3.4 Other Delayed Somatic Effects

Cataract. Chronic and acute exposure of the eyes can lead to cataracts secondary to inducing lens fiber disorganization. Not all radiation is equally effective in producing cataracts; neutrons are much more efficient than other types of radiation. In man the cataractogenic threshold is estimated at 2 – 5 Gy as a single dose or 10 Gy as a fractionated dose. The period between exposure and the appearance of the lens opacities averages 2 – 3 years, ranging from 10 months to more than 30 years [26, 27].

Hypothyroidism. The thyroid gland is exposed to irradiation during radiation therapy of malignant head and neck tumors or the treatment of hyperthyroidism with iodine-131. Patients who received doses of 10 – 40 Gy to the thyroid for the treatment of other malignant diseases developed hypothyroidism a few months to many years after exposure. A lower moderate dose of 10 – 20 Gy can result in hypothyroidism, while 500 Gy or more is required to destroy the thyroid completely.

Aplastic Anemia. Human exposure to radiation can cause aplastic anemia, depending upon the dose and fractionation. Death may be the end result of aplastic anemia. It has been suggested that permanent anemia

is caused by a reduced capability of cellular proliferation due to accumulation of residual injury in stem cells. It is important to realize that when part of the body is irradiated, bone marrow that survives unimpaired will replace what is damaged. If only 10% of active bone marrow escapes irradiation, mortality can be decreased from 50% to zero, based on animal studies.

23.6 Exposure from Medical Procedures

For medical radiation, the chest X-ray delivers 0.1 – 0.2 mSv to the chest wall and the gallbladder series approximately 0.25 rem (Table 23.4). The average nuclear medicine procedure delivers 3 mSv to the whole body. The absorbed dose from the C-14 urea breath test is equivalent to that received during a 1-h flight. When these values are compared with those of natural sources of radiation, particularly cosmic rays, which deliver an average of 3.6 mSv/year in the United States and are higher in certain areas, the real magnitude of the low level of radiation can be appreciated. These levels of exposure from diagnostic medical procedures have no detectable biological effects. It is estimated that less than 0.006% of those undergoing nuclear medicine procedures in the United States might be affected annually. PET studies deliver higher doses to the patient to compensate for the short half-life of positron-emitting radioisotopes. Because these radioisotopes are of high energy and prepared in high initial dosing to account for the rapid decay, PET technologists, radiopharmacists and workers at cyclotrons are usually exposed to higher doses than other workers in the nuclear medicine field.

Therapeutic applications of radioisotopes involve not only malignant but also benign conditions, such as hyperthyroidism and arthroplasty, and are widely expanding. In the treatment of thyroid cancer, large doses of iodine-131 may cause depression of bone marrow. For example, 3.7 GBq of iodine-131 delivers 0.5 – 1 Gy to the hematopoietic system, simulating an effect of external whole body radiation.

Table 23.4. Absorbed radiation dose from common natural and medical sources

Source	Radiation dose [mSv (mrem)]
Diagnostic X-ray procedures	
Chest X-ray	0.1 – 0.2 (10 – 20)
Intravenous pyelogram	2.5 (250)
Mammography (one film)	4 (400)
Gallbladder series	5.3 (530)
Panoramic dental X-ray	9 (900)
X-ray CT of the head	58 (5800)
Barium enema series	80 (8000)
Diagnostic nuclear medicine procedures	
^{99m}Tc-DTPA lung ventilation study	0.15 – 0.25 (15 – 25)
^{99m}Tc-MAA lung perfusion study	1.1 (110)
^{99m}Tc-MDP bone scan (20 mCi)	3.6 (360)
^{201}Tl study (2 mCi)	5 (500)
Natural sources	
Two-hour flight	0.05 (5)
Drinking water	0.05 (5)
Natural gas at home (mainly radon)	0.09 (9)
Radionuclide in human body	0.39 (39)
Cosmic radiation	
at sea level)	0.36 (36)
at 2000 m)	5 (500)

23.7 Possible Positive Health Effects

Recently, positive health effects have been noted, i.e., decreased mortality and decreased cancer rates, in human populations exposed to low-level radiation and reported in large studies [28, 29]. Several studies were carried out to compare areas of high background to those with low radiation. Lower cancer incidence and/or mortality rates in the former were the finding in many such studies in China [30], India [31], Iran [32] and the USA [33]. It has to be noted, however, that this form of epidemiological study does not compare the individual's radiation exposure to cancer rate; therefore strong conclusions cannot be based solely on such studies. On the other hand, none of these studies has found a higher cancer incidence in high background radiation zones. An epidemiological study [34] comparing cancer mortality in Canada's nuclear industry workers to that in non-radiation workers has found similar favorable effects for low-radiation exposure. The former group of workers had a cancer mortality of 58% of the national average as compared to 97% of that in the latter. Cohen [11] studied the relationship between lung cancer death rates and residential radon gas in the USA. He found that lung cancer decreased for increments in radon levels. These findings were consistent even after reanalysis and correction for confounding factors such as smoking. To date, there is considerable debate regarding this study.

23.8 Summary

Several biological effects can result from ionizing radiation. These can be due to direct or indirect mechanisms, and they can be acute or delayed. Acute effects occur with exposure to high-level radiation. Delayed effects may appear after a long time and include cancer, genetic effects, effects on the unborn child, and other effects such as cataracts and hypothyroidism. Based on

our current knowledge, no level of exposure to radiation can be described as absolutely safe and no level is uniformly dangerous. Radiation doses have to reach a certain level to produce acute injury but not to cause cancer or genetic damage. No biological effects in individuals have ever been documented as being due to levels of ionizing radiation employed for medical diagnosis. Absorbed doses from nuclear medicine procedures are very low. Fear of radiation must not be permitted to undermine the great value of radiation in clinical practice. However, safe handling of all levels of radiation is important to prevent or minimize possible biological effects.

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